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Method for reducing phase errors due to CCD nonlinearity

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ABSTRACT

The three-step phase-shifting and mean value methods are combined to reduce phase errors due to charge coupled device (CCD) nonlinearity. The CCD nonlinearity induced phase error value is obtained by combining the output fringe intensity phase values obtained from ideal and nonlinear CCD after phase unwrapping. Assuming CCD nonlinearity, the new phase value is offset by $\pi/3$ from the ideal CCD result. The mean of the new and original phase error values yields the final phase error value. The CCD nonlinearity induced phase errors are significantly reduced using our method than with previous methods. Computer simulation and experimental results verify the correctness of the basic principle analysis.

1. Introduction

Phase measurement plays an important role in optical non-contact automated three-dimensional (3D) object shape measurement. It is also widely used in such fields as machine vision, solid modeling, automated industrial testing equipment, and medical diagnostics [1–11]. Phase measurement is generally performed using the phase-shifting method [1–3] and the Fourier transform method [4,5]. Of these, the phase-shifting method and the three-step phase-shifting method in particular, has been researched widely [6–10]. For instance, Pan et al. have developed a three-step color phase-shifting technique for measurement of dynamic 3D object shapes and obtained precise measurement results [6]. Chung et al. have presented a novel three-step color phase-shifting method for 3D shape measurement that involves a combination of phase-shifting and phase-unwrapping processes [7]. Further, Pan et al. have derived a mathematical model of phase measurement errors in commonly used three- and four-step phase-shifting algorithms, and proposed an algorithm to compensate for the phase error [8]. Huang et al. have proposed the 3 + 3 phase-shifting algorithm, which is based on digital fringe projection and phase-shifting techniques, in order to reduce the measurement error in 3D shape measurement systems [9].

Several scholars studying the phase-shifting method have focused on the phase error caused by a projector's gamma nonlinearity [10,11]. For example, Xiao et al. have proposed a robust gamma correction method that renders the captured fringe patterns well-sinusoidal and alleviates the phase errors caused by the gamma nonlinearity [10]. Further, Zhang et al. have described a novel phase error compensation method to reduce the phase error caused by nonsinusoidal waveforms. Their method is based on the finding that nonsinusoidal waveforms depend on a projector's gamma nonlinearity only [11]. Although these proposed nonlinearity correction methods can improve phase accuracy to a certain degree, further improvement for applications requiring very high accuracy can be achieved by reducing the charge coupled device (CCD) nonlinearity effect, which has not yet been adequately studied [5,12].

Therefore, in this paper, we present a method for reducing the CCD nonlinearity induced phase error. In practice, phase measurement is realized from the deformed fringe of a reference plane and an actual object acquired by CCD. When the three-step phase-shifting method is employed, the CCD nonlinearity effect results in phase errors that affect the precision of the phase measurement of a 3D object shape. To reduce these phase errors, we apply the three-step phase-shifting method twice, by combining the phase-shifting method with the mean value method. Here, we present computer simulated and experimental results to verify the correctness of the basic principle analysis.

2. Basic principle

CCD is a semiconductor photoelectric device that converts light energy into electric energy [12–14]. Under ideal conditions, there is a linear relation between the output and input light intensities from

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the CCD, and the output light intensity is manifest in the output deformed fringe.

We take $I(x,y)$ as the deformed fringe light intensity output from a CCD camera system under ideal conditions, with $\varphi(x, y)$ being the phase modulation caused by the object height distribution $h(x, y)$. According to Ref. [14], the relationship between $h(x, y)$ and $\varphi(x, y)$ is given by

$$\varphi(x, y) = \frac{-2\pi f_0 d}{L_0 - h(x, y)} h(x, y) \tag{1}$$

where d is the distance between p_2 and I_2, L_0 is the distance between I_2 and O, and f_0 is the spatial carrier frequency of the projection grating along the x axis; these parameters are shown in Fig. 1 of Ref. [14]. In the three-step phase-shifting method, the deformed fringe light intensity from the CCD camera system can be described as [11,15]:

$$I_i(x, y) = a + b\cos\left[\varphi(x, y) + i\frac{2\pi}{3}\right] \quad i = 1,\ 2,\ 3 \tag{2}$$

where a and b are constants.

After the phase unwrapping in Eq. (2), the phase value can be obtained as [11,15]:

$$\varphi(x, y) = \arctan\left\{\sqrt{3}\frac{I_1(x, y) - I_3(x, y)}{2I_2(x, y) - [I_1(x, y) + I_3(x, y)]}\right\} \tag{3}$$

Under actual physical conditions, the CCD nonlinearity effect may lead to a two-step nonlinearity relation between the output and input light intensities. Then, the output deformed fringe light intensity from the CCD can be expressed as [5]

$$I_i'(x, y) = e_0 + e_1 I_i(x, y) + e_2 I_i^2(x, y) \tag{4}$$

If $a = b = M$ in Eq. (2), from Eqs. (2) and (4), we can obtain

$$I_i'(x, y) = \left(e_0 + e_1 M + \frac{3}{2}e_2 M^2\right) + \left(e_1 M + 2e_2 M^2\right) \times \cos[2\pi f_0 x + \varphi(x, y)] + \frac{e_2 M}{2}\cos[2\pi f_0 x + \varphi(x, y)] \tag{5}$$

Supposing that $e_0 + e_1 M + (3/2)e_2 M^2 = U$, $e_1 M + 2e_2 M^2 = V$ and $e_2 M/2 = W$ are constants from Eq. (5), the light intensity of each fringe image in the three-step phase-shifting can be expressed as

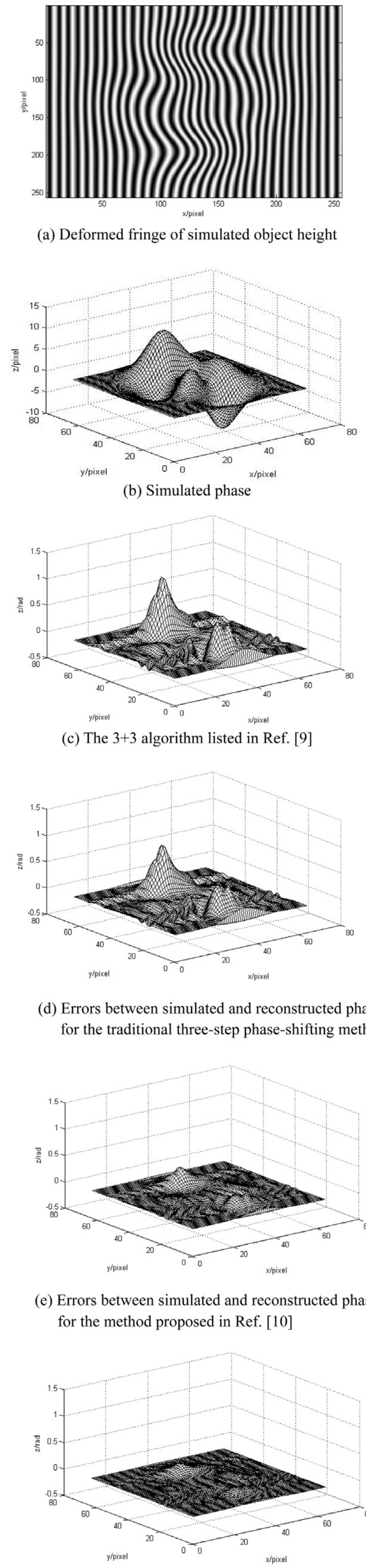
$$I_i'(x, y) = U + V\cos\left[\varphi(x, y) + i\frac{2\pi}{3}\right] + W\cos\left\{2\left[\varphi(x, y) + i\frac{2\pi}{3}\right]\right\} \quad i = 1,\ 2,\ 3 \tag{6}$$

Further, the phase value after phase unwrapping can be expressed as

$$\varphi'(x, y) = \arctan\left\{\sqrt{3}\frac{I_1'(x, y) - I_3'(x, y)}{2I_2'(x, y) - [I_1'(x, y) + I_3'(x, y)]}\right\} = \frac{V\sin[\varphi(x, y)] - W\sin[2\varphi(x, y)]}{V\cos[\varphi(x, y)] + W\cos[2\varphi(x, y)]} \tag{7}$$

Comparing Eq. (3) with Eq. (7), the tangent value of the phase error after phase unwrapping can be obtained as

$$\tan[\Delta\varphi(x, y)] = \tan[\varphi'(x, y) - \varphi(x, y)] = \frac{\tan[\varphi'(x, y)] - \tan[\varphi(x, y)]}{1 + \tan[\varphi'(x, y)]\tan[\varphi(x, y)]} = -\frac{W\sin[3\varphi(x, y)]}{W\cos[3\varphi(x, y)] + V} = -\frac{\sin[3\varphi(x, y)]}{\cos[3\varphi(x, y)] + K} \tag{8}$$



(a) Deformed fringe of simulated object height

(b) Simulated phase

(c) The 3+3 algorithm listed in Ref. [9]

(d) Errors between simulated and reconstructed phases for the traditional three-step phase-shifting method

(e) Errors between simulated and reconstructed phases for the method proposed in Ref. [10]

(f) Errors between simulated and reconstructed phases for our method

Fig. 1. *Simulation results.* (a) Deformed fringe of simulated object height, (b) simulated phase, (c) the 3 + 3 algorithm listed in Ref. [9], (d) errors between simulated and reconstructed phases for the traditional three-step phase-shifting method, (e) errors between simulated and reconstructed phases for the method proposed in Ref. [10] and (f) errors between simulated and reconstructed phases for our method.